Long-term no-till as a means to maintain soil surface structure in an agroecosystem transformed to irrigation

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Highlights

- Soil management is key to avoid soil degradation in areas transformed to irrigation.
- Lower stability of aggregates led to soil crusting under conventional tillage.
- Long-term no-till enhanced aggregate stability and corn early development.
- No-till must be sustained in soils changed to irrigation prone to crust formation.

Abstract

The aim of this study was to determine the most appropriate soil management to reduce the structural degradation of soils susceptible to crusting in Mediterranean areas recently transformed to irrigation. A long-term field experiment (LTE) under rainfed conditions was established in 1996 in NE Spain to compare three tillage systems (no-tillage, NT; reduced tillage, RT; conventional tillage, CT). The experiment was transformed to irrigated corn in 2015. In 2015, an adjacent experiment with the same layout was created (short-term experiment, STE) in an area previously managed under long-term NT. The study was carried out during the second corn growing season (i.e. year 2016). Soil samples were collected from 0-5 cm depth at different dates during corn season. Dry and water-stable macroaggregates and their C concentration, soil organic carbon (SOC) and labile C concentration, soil respiration, bulk density, penetration resistance (PR), water infiltration, macroporosity, microporosity, amount of crop residues and ground cover, corn development, aerial biomass, and grain yield were measured. In LTE and STE tillage led to a breakdown of dry sieved aggregates (of 2-4 and 4-8 mm size) in RT and CT, being slowly reconsolidated throughout the corn growing season. However, macroaggregate water-stability did not increase in CT and RT compared to NT due to a lower SOC concentration, making the soil more susceptible to its degradation by the action of water. SOC differences between treatments were more pronounced in LTE than STE given the long-term differential management in the first, which allowed greater accumulation of SOC under NT. In LTE, PR values between corn rows were greater under NT and non-significantly different within the row. In the case of STE, PR values increased over time after tillage (CT and RT) to match NT in the last sampling. Crop establishment was slower in CT than NT in LTE highlighting the impact of soil surface degradation on crop development. However, and despite in 2015 there were differences in corn yield, a careful planting in 2016 led to the lack of differences between tillage systems on corn yield. Our results indicate that in areas transformed to irrigation intensive tillage leads to greater susceptibility to soil structural degradation. Thus, in these areas the adoption of conservation agriculture practices such RT and NT enhances soil resilience to degradation processes and ensures an adequate development of the crop.

Keywords

Corn; soil degradation; soil crust; tillage systems; transformation to irrigation.

1. Introduction

Soil management practices affect both soil surface characteristics and crop productivity. Tillage exposes soil to erosive agents such as wind and water, inducing its degradation. Under severe erodible forces, soils are exposed to the impact of water-drops, either produced by irrigation or by rainfall. This last process results in the release of organic matter and, generally, in soil crusting (Awadhwal and Thierstein, 1985). In bare soils, structural crusts are a major problem facing many agricultural areas worldwide (Mbuvi et al., 2009). Structural crusts, developed on soil surface, negatively affect seedling emergence and reduce infiltration, favoring runoff and soil erosion (Bately and Davies, 1971). Furthermore, crusting is closely related to soil aggregation. In that sense, Bouaziz et al. (1990) found a linear relationship between soil aggregate size and the proportion of non-emerged wheat seedlings due to soil crusting.

In Mediterranean climate regions, an increasing number of rainfed areas are transformed to irrigation to stabilize or increase crop yields (Apesteguía et al., 2015). This conversion generates significant consequences in agroecosystems. Greater biomass production by irrigation leads to an increase in crop residues which can be returned to the soil. The increase of organic C inputs to the soil usually entails an increase in soil organic carbon (SOC) (Moldenhauer et al., 1994) and, concomitantly, an improvement in soil quality (Wick et al., 1998). Moreover, C inputs play an essential role in the formation of soil aggregates, which physically protect SOC from microbial degradation (Beare et al., 1994) boosting SOC sequestration and climate change mitigation (Lal, 2011).

C-enriched aggregates are more stable to alterations such as rainfall, irrigation or tillage. Furthermore, crop residues protect the soil surface, preventing the formation of crusts (Ekern, 1950). Besides its importance in the Mediterranean climate regions, the impact of rainfed to irrigation transformation on soil surface characteristics (e.g., soil aggregation, soil organic carbon, bulk density, infiltration, penetration resistance and soil porosity) has been scarcely studied. Regarding to this, Apesteguía et al. (2015) observed an increase of the proportion of large macroaggregates under corn and wheat cropping systems managed under conventional tillage (chisel plow) when transforming a Mediterranean rainfed area to irrigation in north of Spain. Also, in Central Great Plains, Denef et al. (2008) found greater SOC storage in the surface soil layer (0–20 cm) in pivot-irrigated areas compared to dryland areas.

Tillage operations that incorporate crop residues into the soil increase soil susceptibility to degradation. When intensive tillage systems are adopted, soil remains bare until the next planting. Bare soils result more exposed to erosive agents and to drop impact promoting soil surface sealing and crusting and, at the end, water runoff (Pagliai, 2003). Tillage generally decreases soil bulk density compared to no-tillage (NT) (Lal, 1999) and it can negatively influence soil water infiltration, depending on soil type and properties. For instance, Chan and Heenan (1993) and McGarry et al. (2000) reported lower infiltration rates under conventional tillage (CT) compared to NT. The adoption of NT systems has been identified as an optimal practice to reduce soil degradation and to improve soil aggregation in rainfed Mediterranean areas (Álvaro-Fuentes et al., 2009; Plaza-Bonilla et al., 2010). Moreover, it has been proved that long-term use of NT increases soil organic carbon (SOC) sequestration (Plaza-Bonilla et al., 2015). Similarly, Follett et al. (2013) showed that CT induced greater losses of old organic matter than NT in irrigated maize systems influencing soil physical properties.

In Mediterranean irrigated agroecosystems, typical soil management strategies include intensive tillage with deep subsoilers and mouldboard ploughs. However, unlike in irrigated systems, in Mediterrenan rainfed areas an increasing adoption of minimum tillage (MT) or NT techniques has been taking place over the last 30 years (Lampurlanés et al., 2016). In Mediterranean irrigated areas, the limited knowledge associated to the use of MT or NT systems, makes farmer adoption difficult and jeopardizes the soil quality benefits attained with long-term NT. As a consequence, the aim of this study was to determine to what extend soil management practices affect soil surface characteristics and crop establishment when transforming a rainfed area to irrigation in Mediterranean conditions.

2. Materials and methods

2.1 Experimental design

A field experiment was conducted in Agramunt, NE Spain (41°48′ N, 1°07′ E, 330 m asl), where the soil was classified as Typic Xerofluvent (Soil Survey Staff, 2014). Soil characteristics are presented in Table 1. The climate is semiarid Mediterranean with a mean annual precipitation of 430 mm and a potential evapotranspiration of 855 mm. Mean annual air temperature is 13.8°C.

A rainfed long-term field experiment (LTE) was established in 1996 to compare three tillage systems (no-tillage, NT; reduced tillage, RT; conventional tillage, CT) under barley monocropping (Angás et al., 2006). In 2015 the LTE experiment was transformed to irrigation with solid set sprinklers and corn (*Zea mays* L.) monoculture as cropping system. After the transformation to irrigation, the LTE experiment maintained the same tillage treatments (NT, RT and CT) and the same experimental layout as the previous rainfed experiment. At the same time, in 2015, a new tillage experiment was created adjacent to the LTE experiment (separated by a 15-m corridor). The layout of this new experiment (so called short-term experiment, STE) was exactly the same as the LTE (same tillage treatments, spatial arrangement and cropping system) but with different historical tillage management. For the last 20 years, the entire surface occupied by the STE experiment consisted of a rainfed NT winter cereal system. The experimental design in both LTE and STE consisted in a randomized block design with three replications and plot size of 50x6 m.

In LTE and STE, the CT treatment was implemented according to the traditional practices of the area. It consisted of one pass of rototiller to 15 cm depth followed by subsoiler to 35 cm depth and to finish one pass of a disk plough to 20 cm depth with almost 100% of the crop residues incorporated into the soil. The RT treatment consisted of one pass of a strip-till implement on the corn planting row to 30 cm depth reducing the total area tilled to ca. 20 %. Finally, the NT treatment consisted of weed control with a non-selective herbicide (i.e. glyphosate) at 1.5 L ha^{-1}. Tillage operations were conducted at the end of March and beginning of April 2016 (Table S1) Planting was carried out with a NT machine with disk openers maintaining the same planting depth across tillage systems. Planting of corn (cv. Kopias) was performed on 22 April, at a rate of 90.000 seeds ha^{-1} with the rows 0.73 m apart. Mineral N fertilization was split in one pre-planting application of 50 kg N ha^{-1} with urea (46% N), on 12 April, and two top-dressing applications of 75 kg N ha^{-1} with calcium ammonium nitrate (27% N), on 31 May and 5 July, respectively. P and K fertilization consisted of 154 kg ha^{-1} P_2O_5, and 322 kg ha^{-1} K_2O applied at pre-planting, respectively. Irrigation was supplied to meet the estimated evapotranspiration of the crop and effective precipitation. Irrigation began on 19 April and ended on 14 September with a total of 77 irrigation dates. The amount of water applied by irrigation was 672 mm. Harvesting was done by the end of October with a commercial combine which chopped and spread the crop residues over the soil. The fallow period was maintained free of weeds with an application of glyphosate at 1.5 L ha^{-1}.

2.1.1 Soil and crop samplings and analyses

Soil and crop measurements were carried out during the corn growing season of 2016, at the next key dates: before tillage operations, right after planting, two weeks later and one month after planting, and right before corn harvest (Table S1). In the first two measurement dates, all variables except soil porosity were measured. Moreover, a weekly monitoring of crop development was carried out on two sampling areas of 2.5 x 2.5 m per plot.

2.1.2 Soil water-stable macroggregates, bulk density, moisture, organic C fractions, and soil respiration.

From each plot, two composite soil samples, one within the row (WR) and one between the rows (BR), were prepared from two samples taken randomly from 0- to 5-cm soil depth using a flat spade and stored in crush-resistant airtight containers. Additionally, soil cylinders to 5-cm depth were obtained to quantify soil bulk density (BD) and soil moisture by drying the samples at 105°C during 48 h until constant weight (Grossman and Reinsch, 2002). Once in the laboratory, unaltered soil samples were gently passed through an 8-mm sieve and air-dried at room temperature. Water-stable macroaggregate size separation was performed using a method adapted from Elliott (1986). Briefly, 100 g of the 8-mm sieved soil was placed on the top of a 2-mm sieve and submerged for 5 min in deionized water at room temperature. The sample was manually sieved 50 times for 2 min to achieve aggregate separation. The slurry was further sieved through a 0.250 mm sieve using the same procedure. Therefore, two aggregate-size fractions were obtained: large water-stable macroaggregates (2–8 mm) and small water-stable macroaggregates (0.250–2 mm). Soil aggregates were oven-dried at 50°C during 48 h in aluminum trays and weighed. Sand correction was performed to each aggregate size according to Elliott et al. (1991) since sand was not considered to be part of the aggregates. Sand content was determined by dispersing a 5 g subsample in a sodium hexametaphosphate solution (5 g L^{-1}) using a reciprocal shaker, sieved with the corresponding sieve, oven-dried at 50°C during 24 h and weighed. Furthermore, the dry aggregate size distribution was conducted placing 100 g of air-dried sub-sample (8 mm sieved) on an electromagnetic sieve apparatus (Filtra FTL-0200, Badalona, Spain) with a series of sieves (4, 2, 1, 0.25 and 0.05 mm). A sieving time of 1 min and the lowest power program of the machine were used.

Two fractions of organic C of the bulk soil were determined: the permanganate-oxidizable organic C (POxC) and the dichromate oxidizable soil organic C (SOC). SOC concentration of each water-stable aggregate-size fraction was also quantified. POxC was quantified according to the method of Weil et al. (2003), while SOC was determined using the wet oxidation method of Walkley & Black described by Nelson and Sommers (1996). This last method was modified to increase the digestion of SOC, heating the sample externally at 150 °C for 30 min.

Soil respiration (SR) was measured in LTE using non-steady state static chambers (Hutchinson and Mosier, 1981). Gas samples were taken at 0, 20 and 40 min after the closure of the chamber and stored in vials, being subsequently analyzed by a gas chromatography system equipped with a flame ionization detector coupled to a methanizer. Gas fluxes were calculated taking into account the linear increase of CO_2 within the chamber with time (40 min) and correcting the values for air temperature (Holland et al., 1999).

2.1.3 Soil penetration resistance and water infiltration.

Soil penetration resistance (PR) was measured using a pocket penetrometer (Facchini srl. mod. FT 327, Alfonsine, Italy). The apparatus consists of a short rod finishing in a tip which penetrates at a constant rate up to a depth of 5 cm. Four randomly selected points were measured in each sampling area and position (WR, BR).

The rate of soil water infiltration (SWI) was quantified near saturation with a disc permeameter (CSIRO Permeameter, A.L. Franklin Precision Engineers) similar to the design of Perroux and White (1988), used to carry out ponded measurements (positive water potentials). One measurement per plot was performed on each sampling date. The level of water infiltrated was measured every ten seconds for the first two minutes and every one minute until a steady state was reached.

2.1.4 Soil macroporosity, microporosity and total porosity.

Undisturbed soil samples (0-5 cm depth) were taken in each plot using stainless steel cylinders of known volume. In the laboratory, the samples were placed in porous ceramic plates to saturation. After saturation, the samples were weighed (saturated weight) and left in the same ceramic plates at -10 kPa for 24 h to drain all water not hold against the gravitational force. They were weighed again and the difference with the saturated weight divided by the sample volume was the fraction of soil volume corresponding to macropores or macropore porosity (MaP). Later, the samples were dried at 105 °C. The difference between the saturated and dried weight divided by the sample volume, was the fraction of soil volume corresponding to pores or total porosity (TP). The difference between TP and MaP was the fraction of soil volume corresponding to the micropores or micropore posority (MiP).

2.1.5 Crop residues and corn early development, biomass and grain yield.

The proportion of soil surface covered by crop residues was estimated (i) before planting (for NT and RT, since crop residues were already incorporated in the soil in CT) and (ii) right after harvest. The measurements were done using four metal grids of 0.25 m^2 per plot divided into 0.25 x 0.25 m squares (CIAT, 1982) . Afterwards, the residues within the grids were oven-dried at 60 °C during 48 h and weighed.

The monitoring of the corn emergence and early development was carried out once a week from planting to V6 by counting the number of plants per row (2 m) and recording their phenological stage (Ritchie et al., 1997).

Corn above-ground biomass and grain yield were determined in mid-October by cutting the plants at the soil level along 2 m of two central rows of each plot. The number of plants and ears was counted and registered. Afterwards, a sub-sample of two entire plants and five ears were taken, oven-dried at 60°C for 48 h and weighed. Next, the grain was threshed and weighed. Grain yield was adjusted to 14% moisture.

2.3 Statistical analyses

For each experiment (LTE and STE), analysis of variance were performed with tillage, sampling position, sampling date and their interaction as effects. For variables measured under different soil moisture levels (SWI, PR and BD), soil moisture was added to the ANOVA as co-variable. When significant, differences among treatments were identified at 0.05 probability level of significance with a protected t-Student test. A Sqrt-transformation was carried out to normalize BD, SWI (LTE and STE), sand-free large water stable macroaggregate-POxC (2-8 mm) (STE) and dry aggregate size distribution (4-8 mm) (LTE) data. All the statistical analysis were performed with the statistical package JMP 12 (SAS Institute Inc, 2016).

3. Results

Rainfall, irrigation events and air temperature during the entire experimental period are shown in Fig. 1. Air temperature increased from the beginning of the experimental period, reaching a maximum in summer months (July-August), to decrease later during autumn months. Total rainfall during the growing period was 140 mm with the greatest rainfall recorded in May (26 mm), which was far from the evapotranspiration needs. The amount of water applied by irrigation was 672 mm, which meant that the crop received a total of 812 mm of water during the growing period.

3.1 Soil management effect on water infiltration, soil penetration resistance (PR), macroporosity (MaP), microporosity (MiP), total porosity (TP) and bulk density (BD) dynamics.

In the STE experiment, the interaction between tillage, sampling date and position significantly affected PR (Table 2). In the case of the LTE experiment, PR was significantly affected by the interaction between tillage and position and between sampling date and position. SWI, MaP, MiP and TP showed significant differences between sampling dates in LTE (Table 2). However, in STE differences between sampling dates were only observed on TP. BD was significantly affected by tillage, sampling date and the interaction between sampling date and position in LTE and by tillage and the simple effect of sampling date in STE (Table 2).

In the STE experiment and for the three sampling dates right after tillage, NT showed greater PR in the BR position than the other two treatments (Fig. 2b). The lowest PR values were found in the WR position in the second sampling date, just after tillage (1.38, 1.54 and 1.13 kg cm^{-2} for NT, RT and CT, respectively). However, the highest PR values were found in the BR position in the last sampling date, seven months after the first measurement (17.31, 15.04 and 14.94 kg cm^{-2} for NT, RT and CT, respectively) (Figs. 2a and 2b). In LTE, PR showed significant differences between tillage treatments in the BR position, being greater under NT (13.19 kg cm^{-2}) than under RT (10.55 kg cm^{-2}) and CT (11.09 kg cm^{-2}), as an average of all five sampling dates. Contrarily, tillage treatments showed similar PR in the WR position. Significant differences in PR between sampling dates and sampling positions were also observed in LTE, being greatest in the fifth sampling date in both positions with values of 19.0 and 10.2 kg cm^{-2} for BR and WR, respectively.

As an average of sampling dates and positions, BD was greater under NT (1.47 and 1.49 g cm^{-3} for LTE and STE, respectively) than RT (1.36 and 1.40 g cm^{-3} for LTE and STE, respectively) and CT (1.43 and 1.33 g cm^{-3} for LTE and STE, respectively). No significant differences were found between tillage treatments on SWI in neither LTE nor STE (Table 2). Mean SWI values were 3.14, 2.40 and 1.70 mm h^{-1} for NT, RT and CT, respectively, in the LTE, and 3.80, 3.60 and 2.60 mm h^{-1} for the same tillage treatments in the STE.

3.2 Soil management effect on water-stable macroaggregate and dry aggregate distribution dynamics.

In the LTE experiment, the interaction between tillage and sampling date significantly affected sand-free water-stable macroaggregates (0.250-2 and 2-8 mm sizes). However, in the STE experiment, small water-stable macroaggregates were only affected by tillage (Table 3). In LTE the proportion of large sand-free water-stable macroaggregates decreased from the second sampling date (just after tillage) up to the fourth sampling date (Table 4). However, in the last sampling (just before harvest), the proportion of large sand-free water-stable macroaggregates was not different to the first sampling value. In this same experiment, the proportion of small sand-free water-stable macroaggregates only showed significant differences between tillage treatments in the first and fourth sampling dates. In these two sampling dates, small sand-free water-stable macroaggregates were greater in CT compared to RT and NT (Table 4). In the STE experiment, a greater proportion of small sand-free water-stable macroaggregates was observed under NT and RT (0.42 and 0.41 g g^{-1}, respectively) compared to CT (0.35 g g^{-1}) as an average of sampling dates and positions.

In the LTE and STE experiments, most dry aggregate sizes were significantly affected by the tillage x sampling date interaction (Table 3). In both experiments, dry aggregate classes of 4-8 and 2-4 mm size showed significant differences between tillage systems in all the sampling dates except for the last one, and the first one for the 4-8 mm fraction in the STE (Fig. 3). Compared to NT, a decrease in the proportion of dry-sieved aggregates of 4-8 and of 2-4 mm was observed under RT and CT in the second sampling date, after tillage. Average dry-sieved 4-8 mm aggregate values in the second, third and fourth sampling dates were 0.18 and 0.17 g g^{-1} under CT, 0.18 and 0.20 g g^{-1} under RT and 0.31 and 0.20 g g^{-1} under NT in LTE and STE, respectively (Fig. 3). After the fourth sampling date, the proportion of aggregates in RT and CT gradually increased until the last sampling (133 days after tillage) when no differences between tillage systems were observed (Fig. 3). Unlike, the smaller dry-sieved aggregate sizes (i.e., 0.250-1 mm and 0.05-0.250 mm) showed opposite results with greater values under CT and RT than under NT in the first four sampling dates in the LTE and in the second to fourth sampling dates in the STE. Regarding to this, the proportion of this aggregate sizes increased right after the implementation of tillage (second sampling date) in RT and CT in both field experiments.

3.3 Soil management effect on bulk soil organic C, water-stable macroaggregate C and soil respiration.

Bulk SOC concentration was significantly affected by tillage systems and sampling date effects in LTE and also by their interaction in STE (Table 3). In the LTE experiment, the SOC concentration was 21.1, 14.8 and 10.3 g C kg^{-1} soil for NT, RT and CT, respectively, as an average of sampling dates. In the STE experiment, SOC differences between tillage systems were found in all sampling dates (Fig. 4c). SOC concentration followed the order NT>RT>CT in the first sampling date, and showed greater values under NT than CT and intermediate values in RT in the last fourth sampling dates (Fig. 4c). In general, SOC values in CT were about 36% higher in STE compared with LTE, as an average of all sampling dates (Figs. 4a and 4c).

Bulk soil POxC concentration showed significant differences between tillage systems and sampling dates in both field experiments (Table 3). In LTE, POxC concentration decreased in the following order: CT>RT>NT, while in STE NT presented lower bulk soil POxC concentration than CT and RT (Fig. 5).

Not enough water-stable large macroaggregates (2-8 mm) were obtained in the wet sieving procedure for aggregate-C determination. The C concentration of the small size water-stable macroaggregates (aggregate-C) showed significant interaction between tillage and sampling date in the LTE experiment (Table 3). Significant differences between tillage systems were observed in the second sampling date (just after tillage) with greater aggregate-C in CT than NT and intermediate values under RT. Differences also occurred in the last sampling date (right before harvest) with greater values in NT and RT than CT (Fig. 4b). Differently, in the STE experiment, aggregate-C was only affected by the sampling date (Table 3).

The interaction between sampling date and tillage system significantly affected soil respiration (Table 2). Soil respiration increased from the second sampling date (coinciding just after tillage) with values of 615, 504 and 276 mg CO_2-C m^{-2} day^{-1} for RT, NT and CT, respectively, until the last sampling with values of 1203, 940 and 921, mg C-CO_2 m^{-2} day^{-1} for the same tillage treatments. Significant differences between tillage treatments were found in the second, third and fourth sampling dates with CT showing the lowest values (Table 5).

3.4 Soil management effect on corn emergence and early development, crop residues, crop biomass and grain yield.

In the LTE experiment, corn emergence was slower under CT than under NT and RT. In this experiment, 21 days after planting 64,957 emerged plants ha^{-1} were observed under NT, while under RT and CT the plants observed dropped to about 97% and 59% of the NT value, respectively. However, 44 days after planting the number of plants emerged was similar between tillage systems. In contrast, in the STE experiment, corn emergence was similar in the three tillage treatments, with final density values of 70,513, 76,068 and 69,231 plants ha^{-1} in NT, RT, and CT, respectively

In both experimental fields, the proportion of the soil surface covered by crop residues was significantly affected by tillage systems (Table S2). Before planting, the surface covered by crop residues was 86% and 70% for NT and RT, respectively, and 88% and 73% for the same tillage treatments in the LTE and STE experiments, respectively. Seven months later, right before harvest, the proportion of surface covered by residues was 77%, 45% and 10% for NT, RT and CT, respectively, and 81%, 53% and 28% for the same tillage systems in the LTE and STE experiments, respectively.

Corn yield and above-ground biomass were not significantly affected by tillage treatments in any of the field experiments (Table S2). However, in the LTE experiment, a non-significant trend of greater grain yield was observed under NT than CT (11,680 vs. 9,864 kg ha^{-1}).

4. Discussion

4.1 Effect of long-term and short-term management practices on soil surface and corn development.

The different historical management of the two experiments tested had a great impact on the results obtained. In the LTE experiment, soil inversion with moldboard plough for the last 20 years (CT treatment) led to soil crusting (Fig. 6b). However, NT for 20 years provided greater resilience to soil degradation and crust formation, enhancing water infiltration, with almost two-fold greater water infiltration in NT compared to CT.

In the STE experiment, tillage treatments significantly affected PR between corn rows, being the greatest values in NT. However, within corn rows, similar PR values were observed among tillage treatments. Also, greater BD was observed in NT when compared to the rest of treatments in both experiments. Bulk density, penetration resistance and water content in the soil are closely related (Ferreras et al., 2000). Soil PR tends to increase when there is an increase in bulk density (Lampurlanés et al., 2003). However, in our study, PR and BD could not be limiting crop growth, since the highest yields were observed under NT. According to Neave and Rayburg (2007) soil PR is usually related to the presence of soil crusts. Our results suggest that PR was not a good indicator to relate the presence of soil crust with corn development failures since the highest values of PR were measured in NT (Fig. 6a). Therefore, it was necessary to test the performance of other variables as indicators of soil crusting. Soil crusting in CT could be the consequence of a lower cover of soil surface by crop residues than NT, resulting in the degradation of soil aggregates by the impact of water drops of irrigation or rain (Ruan et al., 2001).

In both experiments, tillage operation led to a breakdown of dry-sieved aggregates of greater size (4-8 mm and 2-4 mm). However, during crop growth, the CT and RT treatments showed an increase in the proportion of these 4-8- and 2-4-mm size macroaggregates resulting in no differences with NT by the end of the experiment. This increase in the proportion of soil macroaggregates in RT and CT may be explained by the contribution of organic matter when crop residues are incorporated with tillage.

Fresh organic matter from crop residues activates the aggregation cycle being firstly incorporated into macroaggregates (Six et al., 2000). Although the greater fractions of dry-sieved aggregates in CT and RT increased over time, the proportion of water-stable macroaggregates of size 2-8 mm did not, which demonstrates that the stability of soil structure in those treatments was still lower compared to NT. When using NT, aggregate turnover is decreased, promoting the formation of macroaggregates with higher stability (Álvaro-Fuentes et al., 2009; Panettieri et al., 2013). Consequently, soil aggregates in CT are less resistant to the action of water, either received as irrigation or rainfall. In our experiment, greater SOC concentration was observed in NT compared to RT and CT at the soil surface. The contribution of crop residues and the stimulation of biological activity leads to the formation of stable macroaggregates in NT (Martens et al., 2004; Tisdall and Oades, 1982). In the same study area, Álvaro-Fuentes et al. (2013) observed higher SOC and microbial activity in surface NT soils compared with CT soils. Also, Cantero-Martínez et al., (2004) observed greater activity of earthworms in the first 30 centimeters of soil when using NT, since this soil management does not alters their activity, favoring their development. In NT, the accumulation of SOC is promoted (Balesdent et al., 1990; Plaza-Bonilla et al., 2013), mainly in the first centimeters of the soil profile (Franzluebbers, 2001; Reyes et al., 2002). It is expected that the increase in SOC and the concomitant improvement of soil biological activity in NT result in higher soil CO_2 emissions to the atmosphere (Reicosky, 2007). In our experiment, the NT treatment presented the highest soil respiration in throughout the study period (only in the first sampling date CO_2 emission values were similar among tillage treatments).

In 2015 (the first year of irrigation and the previous corn season), corn yield was greatly affected by soil degradation. In 2015, significantly lower yield values were found in CT (5,876 kg grain ha^{-1} at 14% moisture) compared to RT and NT (10,649 and 12,747 kg grain ha^{-1} at 14% moisture, respectively). The strong impact of soil crusting on corn yield observed in 2015 motivated us to implement in 2016 an adequate cultipacker-rolling pass just after sowing to break soil crust (in CT and RT) and also to change irrigation management based on short and more frequent irrigation events. These two management changes intended to prevent soil crusting and, consequently, yield losses. According to the results presented in this study, these strategies successfully avoided yield losses in 2016. Despite corn emergence was earlier under NT and RT than CT in both experiments, 44 days after planting the number of corn plants were similar among tillage systems. Interestingly, despite the impact of tillage treatments on soil surface structure, the implementation of a successful planting led to the same yield between treatments. Similar to our results, after two years of study, Alletto et al. (2011) observed a delay in corn development in CT compared to conservation tillage early in the growing season when assessing the impact of soil management and cover crops in corn production in an irrigated area in SW France. The last authors related the delay in corn development to greater soil drying under CT which negatively affected the final corn grain yield.

4.2 Effect of soil management change during the transformation to irrigation on soil surface properties.

In the LTE experiment, two decades of contrasting tillage under rainfed conditions led to different initial soil conditions between tillage treatments when transforming the area to irrigation. The continuous use of CT in the LTE experiment resulted in a decrease in SOC compared with NT and RT as a result of the lower amount of crop residues returned to the soil as C inputs (Morell et al., 2011). In rainfed Mediterranean conditions, the use of NT enhances the amount of water stored in the soil (Lampurlanés et al., 2016), increasing crop biomass and, consequently, C inputs as crop residues. Regarding to this, Virto et al., (2012) demonstrated that SOC storage is mainly explained by the amount of C inputs returned to the soil. In the LTE experiment, the lower SOC levels found in the CT treatment made the soil more susceptible to degradation. However, in the STE experiment, the 20 years of NT management prior to the transformation from rainfed to irrigation and to the setup of the different tillage treatments, favour that differences between tillage systems on SOC concentration were minimal (3.7% difference between NT and CT) making soil surface in the CT treatment more resilient to the impact of water and to its direct impact on soil crusting. The resilience to soil crusting found in the CT plots of the STE contrasted with the susceptibility to crusting and soil surface degradation found in the CT plots of the LTE experiment. Thus, initial SOC concentration and soil surface structural condition played a major role on the response of soil to the transformation from rainfed conditions to irrigation. In general, high SOC levels tends to increase the rate of water infiltration into the soil (Martínez et al., 2008). In our study, although water infiltration did not differ significantly between tillage treatments, a marked trend existed in the rates found between tillage systems, in the next order: NT> RT> CT. Furthermore, infiltration rates were higher in STE than in LTE, coinciding with the greater SOC concentration found in STE compared to LTE. However, water infiltration was quantified by performing ponded measurements, where water movement on the soil surface is impeded. The presence of a soil crust in CT could have increased water runoff, mainly through the surface between rows, which is the preferential route of irrigation water in row crops. This last process would be aggravated by the lack of crop residues on soil surface during the most part of the crop growing period when CT is used. This hypothesis would be supported by our field observations in which soil crusting and the presence of soil sediment prevailed in between rows in the CT treatment of the LTE experiment (Fig. 6b).

5. Conclusions

Our study shows that the long-term use of intensive tillage in areas recently transformed to irrigation leads to a greater susceptibility to soil crust formation, and structural degradation. The results of this study have shown that the main process behind soil crusting was the breakdown of dry aggregates. Although the proportion of dry-sieved aggregates increased after tillage (even reaching similar values than NT at the end of corn growing season) their water stability was lower. Differences in the stability of aggregates between tillage treatments were explained by different SOC levels as a result of long-term (20 years) of contrasted tillage during the previous rainfed conditions in the LTE experiment. By contrast, in the STE experiment, soil structural degradation was minor, given its previous management based on NT which provided higher resilience to soil crusting. The previous NT management during 20 years favoured the stimulation of biological activity and the formation of water-stable macroaggregates in the soil, favoring the early development of the crop. Our data highlights the need to maintain NT over time in rainfed areas transformed to irrigation prone to soil structural degradation, in order to provide the soil enough resilience and ensure an optimum development of crops.

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References

Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Paustian, K., Denef, K., Stewart, C.E., Arrúe, J.L., 2009. Soil aggregation and soil organic carbon stabilization: effects of management in semiarid Mediterranean agroecosystems. Soil Sci. Soc. Am. J. 73, 1519-1529.

Álvaro-Fuentes, J., Morell, F.J., Madejón, E., Lampurlanés, J., Arrué, J.L., Cantero-Martínez, C., 2013. Soil biochemical properties in a semiarid Mediterranean agroecosystem as affected by long-term tillage and N fertilization. Soil Tillage Res. 129, 69-74.

Alletto, L., Coquet, Y., Justes, E., 2011. Effects of tillage and fallow period management on soil physical behaviour and maize development. Agri. Water Manage. 102, 74–85.

Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization-effects on N dynamics and barley yield under semiarid Mediterranean conditions. Soil Tillage Res. 87, 59-71.

Apesteguía, M., Virto, I., Orcaray, L., Enrique, A., Bescansa, P., 2015. Effect of the conversion to irrigation of semiarid Mediterranean drylandagrosecoystems on soil carbon dynamics and soil aggregation. Arid Land Res. Manage. 29, 399-414.

Awadhwal, N.K., Thierstein, G.E., 1985. Soil crust and its impact on crop establishment: a review. Soil Tillage Res. 5, 289-302.

Balesdent, J., Mariotti, A., Boisgontier, D., 1990. Effects on tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. 41, 584-596.

Bately, T., Davies, D.B., 1971. Soil structure and the production of arable crops. J. Agri. Soc. 132, 106–122.

Beare, M.H., Cabrera, M.L., Hendrix, P.F., Coleman D.C., 1994. Aggregate-protected and unprotected organic-matter pools in conventional-tillage and no-tillage soils. Soil Sci. Soc. Am. J. 58, 787–795.

Bouaziz, A., Souty, N., Hicks, D., 1990. Emergence force exerted by wheat seedlings. Soil Tillage Res. 17, 211-219.

Cantero-Martínez, C., Ojeda, L., Angás, P., Santiveri, P., 2004. Efecto sobre la población de lombrices técnicas de laboreo del suelo en zonas de secano semi-árido. Agricultura revista agropecuaria. 866, 724-728.

Chan, K.Y., Heenan, D.P., 1993. Surface hydraulic properties on a red earth under continuous cropping with different management practices. Aust. J. Soil Res. 31, 13–24.

CIAT. 1982. Manual para la evaluación agronómica. Red Internacional de Evaluación de Pastos Tropicales. Toledo JM (ed). Centro Internacional de Agricultura Tropical, Cali, CO, pp. 170.

Denef, K., Stewart, C.E., Brenner, J., Paustian,.K., 2008. Does long-term center-pivot irrigation increase soil carbon stocks in semi-arid agro-ecosystems? Geoderma 145, 121–129.

Ekern, P.C., 1950. Raindrop impact as the force initiating soil erosion. Soil Sci. Soc. Am. J. Proceedings 15, 7-10.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Elliott, E.T., Palm, C.A., Reuss, D.E., Monz, C.A., 1991. Organic-matter contained in soil aggregates from a tropical chronosequence—correction for sand and light fraction. Agric. Ecosys. Envi. 34, 443–451.

Ferreras, L.A., Costa J.L., Garcia, F.O., Pecorari, C., 2000. Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern “Pampa” of Argentina. Soil Tillage Res. 54, 31–39.

Franzlubbers, A.J., 2001. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66, 95-106.

Follett, R.F., Jantalia, C.P., Halvorson, A.D., 2013. Soil carbon dynamics for irrigated corn under two tillage systems. Soil Sci. Soc. Am. J. 77, 951–963.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane JH, Topp GC (eds.), Methods of Soil Analysis. Part 4. Physical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 201–228.

Holland, E.A., Robertson, G.P., Greenberg, J., Groffma, P.M., Boone, R.D., Gosz, J.R., 1999. Soil CO_2, N_2O and CH_4 exchange. In: Roberston, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P., (Eds.), Standard Soil Methods for Long-term Ecological Research. Oxford University Press, New York, pp. 185-201.

Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45, 311–316.

Lal, R., 1999. Long-term tillage and wheel traffic effects on soil quality for two central Ohio soils. J. Sustainable Agric. 14, 67–85.

Lal, R., 2011. Sequestering carbon in soils of agro-ecosystems. Food Policy 36,33-39.

Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., Cantero-Martínez, C., 2016. Long-term analysis of soil water conservation and crop yield underdifferent tillage systems in Mediterranean rainfed conditions. Field Crops Res. 189, 59-67.

Lampurlanés, J., Cantero-Martínez, C., 2003. Soil Bulk Density and Penetration Resistance under Different Tillage and Crop Management Systems and Their Relationship with Barley Root Growth. Am. Soc. Agro. 95,526–536.

Martens, D.A., Reedy, T.E., Lewis, D.T., 2004. Soil organic carbon content and composition of 130-year crop, pasture and forest land-use managements. Global Change Biol. 10, 65–78.

Martínez, E., Fuentes J.P., Acevedo, E., 2008. Carbono orgánico y propiedades del suelo. J. Soil Sc. Plant Nutr. 8, 68-96.

Mbuvi, J.P., Wanjogu, S.N., Kironchi, G., 2009. Characteristics of soil crusts and their influence on some soil properties in Mukogondo catchment, Kenya. Afri. Crop Sci. J. 4, 487–495.

McGarry, D., Bridge, B.J., Radford, B.J., 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Tillage Res. 53, 105–115.

Moldenhauer, W.C., Kemper, W.D., Stewart, B.A., 1994. Long-term effects of tillage and crop residue management. In: Stewart, B.A., Moldenhauer, W.C., (Eds). Crop residue management to reduce erosion and improve soil quality. Conservation Research Report 37. United States Department of Agriculture-Agricultural Research Service. Beltsville, MD, pp. 55-60.

Morell, F.J., Cantero-Martínez, C., Lampurlanés, J., Plaza-Bonilla, D., Álvaro-Fuentes, J., 2011. Soil carbon dioxide flux and organic carbon content: effects of tillage and nitrogen fertilization. Soil Sci. Soc. Am. J. 75, 1874–1884.

Neave, M., Rayburg, S., 2007. A field investigation into the effects of progressive rainfall-induced soil seal and crust development on runoff and erosion rates: The impact of surface cover. Geomorphology 87, 378-390.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Spanks DL et al., (Eds), Methods of Soil Analysis. Part 3. Chemical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 961–1010.

Panettieri, M., Knicker, H., Berns, A.E., Murillo, J.M., Madejón, E., 2013. Moldboard plowing effects on soil aggregation and soil organic matter quality assessed by ^{13}C CPMAS NMR and biochemical analyses. Agric. Ecosys. Envi. 177, 48–57

Perroux, K.M., White, I., 1988. Designs for disc permeameters. Soil Sci. Soc. Am. J. 52, 1205-1215.

Pagliai, M., 2003. Soil surface sealing and crusting-soil compaction. En: College on Soil Physics. Trieste Italy, pp. 24.

Plaza-Bonilla, D., Cantero-Martínez, C., Álvaro-Fuentes, J. 2010. Tillage effects on soil aggregation and soil organic carbon profile distribution under Mediterranean semi-arid conditions. Soil Use Manage 26, 465–474.

Plaza-Bonilla, D., Cantero-Martínez, C., Viñas, P., Álvaro-Fuentes, J. 2013. Soil aggregation and organic carbon protection in a no-tillage chronosequence under Mediterranean conditions. Geoderma 193-194, 76-82.

Plaza-Bonilla, D., Arrúe, J.L., Cantero-Martínez, C., Fanlo, R., Iglesias, A., Álvaro-Fuentes, J., 2015. Carbon management in dryland agricultural systems. A review. Agro. Sust. Develop. 35, 1319-1334.

Reicosky, D.C., 2007. Carbon sequestration and environmental benefits from no-till systems. In: Goddard T, Zoebisch M, Gan Y, Ellis W, Watson A, Sombatpanit S, (eds.). No-till farming systems. Special publication Nº 3 by The World Association of Soil and Water Conservation.

Reyes, J.I., Martínez, E., Silva, P., Acevedo, E., 2002. Labranza y propiedades de un suelo aluvial de Chile central. Boletín N° 18. Sociedad chilena de la ciencia del suelo y Universidad de Talca. IX Congreso nacional de la ciencia del suelo, Talca, CH, 78-81.

Ritchie, S.W., Hanway, J.J., Benson, G.O., Iowa State University. Cooperative Extension Service. 1997. How a corn plant develops. Spec. Rep. 48. Iowa State Univ. of Sci. and Technol. Coop. Ext. Serv., Ames.

Ruan, H.X., Ahuja, L.R., Green, T.R., Benjamin, J.G., 2001. Residue cover and surface-sealing effects on infiltration: numerical simulations for field applications. Soil Sci. Soc. Am. J. 65, 853–861.

SAS Institute Inc. 2016. JMP, 12. SAS Institute, Cary, NC.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Bioch. 32, 2009–2103.

Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC, pp 306.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Virto, I., Barré, P., Burlot, A., Chenu, C., 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry. 108, 17-26.

Weil, R.R., Islam, K.R., Stine, M.A., Gruver, J.B., Samson-Liebig, S.E., 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. Am. J. Alte. Agric. 18, 3–17.

Wick, B., Kühne, R., Vlek, P., 1998. Soil Microbiological Parameters as Indicators of Soil Quality Under Improved Fallow Management Systems in South-Western Nigeria. Plant Soil 202, 97-107.

Figure captions

Fig. 1 Daily air temperature (continuous line), and weekly rainfall and irrigation (grey and black columns, respectively) during the experimental period.

Fig. 2 Soil penetration resistance (PR) dynamics under three tillage treatments (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) within (WR) (a) and between (BR) cornrows (b), in a short-term field experiment (STE). For a given date, different lowercase letters indicate significant differences between tillage treatments at $P< 0.05$. Arrows represent key dates (H, harvest; I, first irrigation; T, tillage; P, planting).

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Fig. 5 Bulk soil permanganate-oxidizable organic carbon (POxC) concentration at 0-5 cm depth in a long-term (LTE) and short-term (STE) field experiment. For a given experiment, different lower case letters indicate significant differences between tillage treatments at $P<0.05$.

Fig. 6 Development of corn in conventional tillage (CT) and no-tillage (NT) 50 days after planting (a) and soil crusting and sediment movement due to irrigation in CT (b) in the long-term tillage experiment (LTE).

Table 1. Soil characteristics of Ap horizon (0-28 cm) at the beginning of the field experiment (1996).

Soil characteristic	
pH	8.5
$EC_{1:5}$ (dS m^{-1})	0.15
Organic matter (g kg^{-1})	9
P Olsen (ppm)	12
K (ppm)	155
Water retention (-33 kPa) (%)	16
Water retention (-1500 kPa) (%)	5
Sand (%)	46.5
Silt (%)	41.7
Clay (%)	11.8

Table 2. Analysis of variance (*P*-values) of soil water infiltration (SWI), penetration resistance (PR), macroporosity (MaP), microporosity (MiP), total porosity (TP), bulk density (BD) and soil respiration CO_2 (SR) as affected by tillage, sampling date, sampling position and their interactions in a long-term (LTE) and short-term (STE) field experiments. Soil moisture was included as a co-variable.

Source of variation	**LTE**							**STE**					
	SWI	**PR**	**MaP**	**MiP**	**TP**	**BD**	**SR**	**SWI**	**PR**	**MaP**	**MiP**	**TP**	**BD**
Tillage (Till)	ns	ns	0.06	0.05	ns	<0.01	0.01	0.09	<0.01	ns	ns	ns	<0.01
Date	0.04	<0.01	0.04	0.04	0.02	<0.01	<0.01	0.09	<0.01	ns	ns	<0.01	<0.01
Position	-	<0.01	-	-	-	ns	-	-	<0.01	-	-	-	ns
Till*Date	ns	ns	ns	ns	ns	ns	0.01	ns	<0.01	ns	ns	ns	ns
Till*Position	-	0.01	-	-	-	ns	-	-	<0.01	-	-	-	ns
Date*Position	-	<0.01	-	-	-	0.04	-	-	<0.01	-	-	-	ns
Till*Date*Position	-	ns	-	-	-	ns	-	-	0.03	-	-	-	ns
Soil moisture	ns	0.07	0.05	0.05	ns	ns	-	ns	ns	ns	ns	ns	ns

ns, non significant

Table 3. Analysis of variance (*P*-values) of sand-free water-stable aggregate classes (2-8 and 0.250-2 mm), dry aggregate size distribution (4-8, 2-4, 1-2, 0.250-1,0.05-0.250, and <0.05 mm), bulk soil organic C (SOC) and permanganate-oxidizable organic C (POxC) concentration, and aggregate-C as affected by tillage, sampling date and sampling position and their interactions in a long-term (LTE) and short-term (STE) field experiments.

Experiment	**Source of variation**	**Aggregate (mm)**		**Dry aggregate size distribution (mm)**						**Bulk soil**		**Aggregate-C (mm)**
		2-8	**0.250-2**	**4-8**	**2-4**	**1-2**	**0.250-1**	**0.05-0.250**	**<0.05**	**SOC**	**POxC**	**0.250-2**
LTE	**Tillage (Till)**	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	ns	<0.01	<0.01	ns
	Date	<0.01	ns	ns	<0.01	ns	ns	<0.01	ns	<0.01	<0.01	<0.01
	Position	ns	0.09	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Till*Date	0.01	0.03	0.04	<0.01	0.01	0.02	0.03	ns	ns	ns	<0.01
	Till*Position	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Date*Position	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Till*Date*Position	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
STE	**Till**	ns	<0.01	<0.01	<0.01	ns	<0.01	<0.01	ns	<0.01	<0.01	ns
	Date	<0.01	<0.01	ns	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Position	ns	ns	ns	0.01	ns	0.08	ns	ns	0.09	ns	ns
	Till*Date	ns	ns	<0.01	<0.01	ns	<0.01	<0.01	ns	0.03	ns	ns
	Till*Position	ns	ns	ns	ns	0.06	ns	ns	ns	ns	ns	0.08
	Date*Position	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Till*Date*Position	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.04	ns

ns, non significant

Table 4. Sand-free water-stable large (2-8 mm) and small (0.250-2 mm) macroaggregates at 0–5 cm soil depth as affected by tillage system (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) and sampling date in a long-term (LTE) field experiment. For a given date and aggregate class, different lowercase letters indicate significant differences between tillage treatments at *P*< 0.05. Different uppercase indicate significant differences between sampling dates at *P*< 0.05.

Sampling date	**Tillage treatment**	**Sand-free water-stable aggregate classes (g g^{-1})**	
		2-8 mm	**0.250-2 mm**
03/01/2016	**NT**	0.23 a	0.22 b
	RT	0.12 b	0.24 b
	CT	0.15 b	0.46 a
	Average	0.17 A	0.29
04/27/2016	**NT**	0.18 a	0.30 a
	RT	0.08 b	0.25 a
	CT	0.09 b	0.30 a
	Average	0.11B	0.26
05/04/2016	**NT**	0.14 a	0.27 a
	RT	0.06 b	0.25 a
	CT	0.08 ab	0.33 a
	Average	0.09 B	0.28
05/25/2016	**NT**	0.15 a	0.26 b
	RT	0.05 b	0.24 b
	CT	0.10 a	0.37 a
	Average	0.09 B	0.29
10/05/2016	**NT**	0.31 a	0.27a
	RT	0.15 b	0.24 a
	CT	0.07 c	0.29 a
	Average	0.18 A	0.27

Table 5. Soil respiration as affected by tillage system (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) and sampling date in a long-term (LTE) field experiment. For a given date, different lowercase letters indicate significant differences between tillage treatments at P< 0.05.

Sampling date	Tillage treatment	Soil respiration (mg CO_2-C m^{-2} day^{-1})
03/01/2016	**NT**	630 a
	RT	540a
	CT	378 a
04/27/2016	**NT**	504 ab
	RT	615 a
	CT	276 b
05/04/2016	**NT**	796 a
	RT	820 a
	CT	442 b
05/25/2016	**NT**	846 a
	RT	722 ab
	CT	56 b
10/05/2016	**NT**	1203 a
	RT	940 ab
	CT	921 a

Fig. 1 Daily air temperature (continuous line), and weekly rainfall and irrigation (grey and black columns, respectively) during the experimental period.

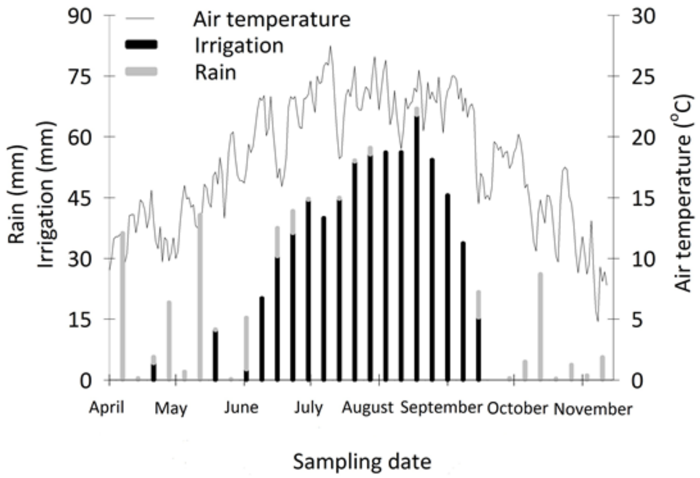

Fig. 2 Soil penetration resistance (PR) dynamics under three tillage treatments (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) within (WR) (a) and between (BR) cornrows (b), in a short-term field experiment (STE). For a given date, different lowercase letters indicate significant differences between tillage treatments at *P*< 0.05. Arrows represent key dates (H, harvest; I, first irrigation; T, tillage; P, planting).

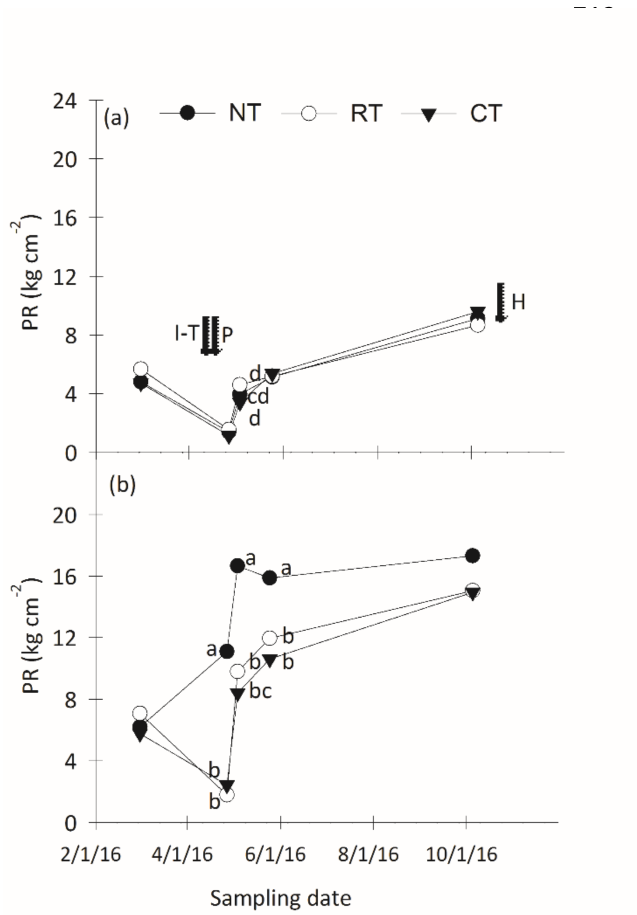

Fig. 3 Dry-sieved aggregate size distribution (4-8, 2-4, 1-2, 0.250-1, 0.05-0.250 and < 0.05 mm) at 0–5cm soil depth as affected by tillage system (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) and sampling date in a long-term (LTE) and short-term (STE) field experiment. For each experiment, aggregate fraction, and sampling date, different lowercase letters indicate significant differences between tillage treatments at *P*< 0.05. Arrows represent key dates (H, harvest; I, first irrigation; T, tillage; P, planting).

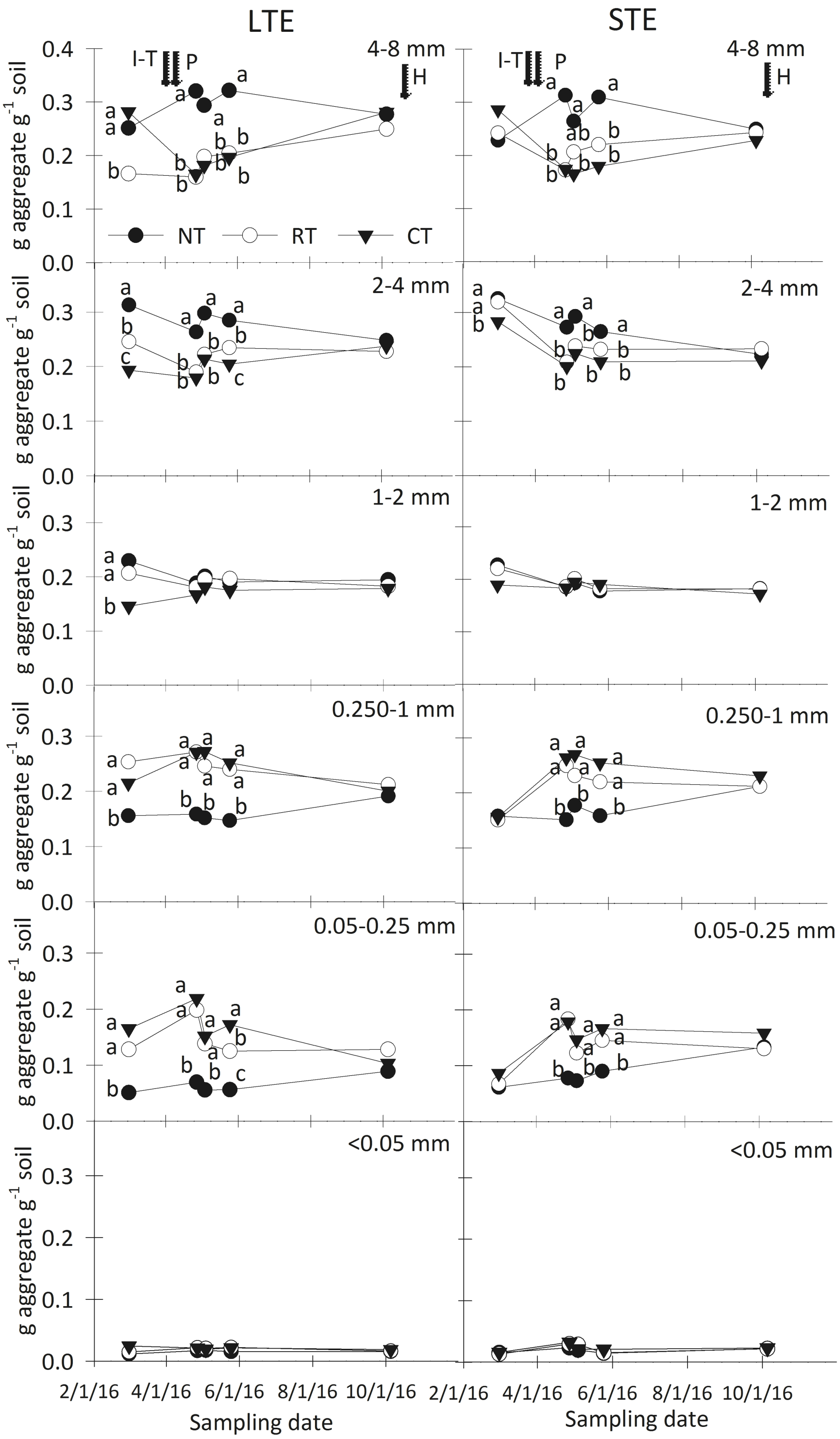

Fig. 4 Bulk soil organic carbon (SOC) and sand-free water-stable small macroaggregate (0.250-2 mm) organic carbon (aggregate-C) concentration at 0-5 cm depth as affected by tillage system (NT, no-tillage; RT, reduced tillage; CT, conventional tillage) in a long-term (LTE) and short-term (STE) field experiments. For each experiment and sampling date, different lowercase letters indicate significant differences between tillage treatments at *P*< 0.05. Arrows represent key dates (H, harvest; I, first irrigation; T, tillage; P, planting).

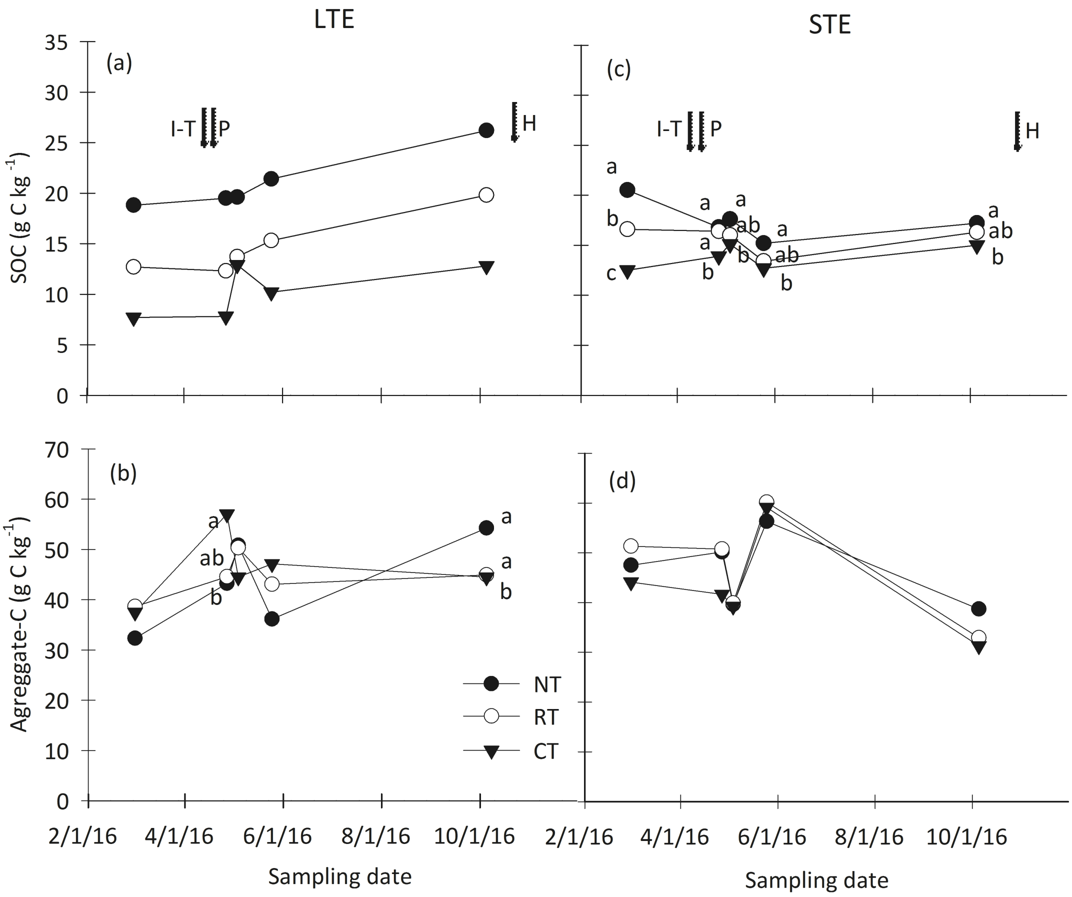

Fig. 5 Bulk soil permanganate-oxidizable organic carbon (POxC) concentration at 0-5 cm depth in a long-term (LTE) and short-term (STE) field experiment. For a given experiment, different lower case letters indicate significant differences between tillage treatments at *P*<0.05.

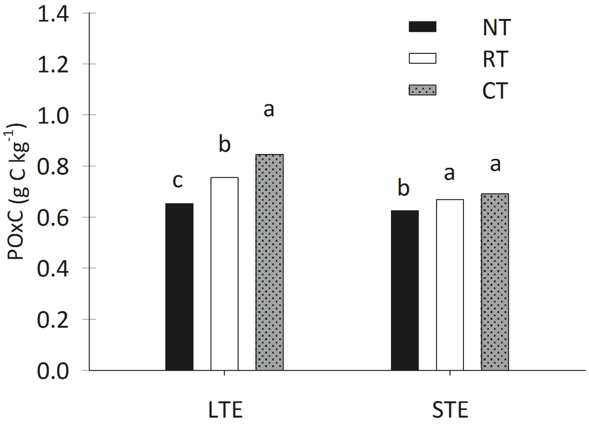

Fig. 6 Development of corn in conventional tillage (CT) and no-tillage (NT) 50 days after planting (a) soil crusting and sediment movement due to irrigation in CT (b) in the long-term tillage experiment (LTE).

Table S1. Sampling and key crop management practices dates in the field experiments. Dates of first and second irrigation are included given its presumable impact on soil consolidation after tillage.

Sampling and crop management practices	**Date**
Soil sampling	03/01/2016
Tillage: Rototiller (CT treatment)	03/07/2016
Tillage: Subsoiler (CT treatment)	03/29/2016
Crop residues sampling	03/30/2016
Pre-planting N fertilization	04/12/2016
Tillage: disk plough and strip-till	04/19/2016
(CT and RT treatments, respectively).	
First irrigation	
Cultipacker-rolling	04/26/2016
Planting	04/26/2016
Second irrigation	05/15/2016
Soil sampling	04/27/2016
Soil sampling	05/04/2016
Macroporosity and microporosity	
Soil sampling	05/25/2016
Macroporosity and microporosity	
First top-dressing N fertilization	06/31/2016
Second top-dressing N fertilization	07/05/2016
Crop residues sampling	10/04/2016
Soil sampling	10/05/2016
Macroporosity and microporosity	
Gran yield and above-ground biomass sampling	10/19/2016
Commercial harvest	11/11/2016

Table S2. Analysis of variance (*P*-values) of crop residues soil cover, grain yield and crop biomass as affected by tillage and sampling date and their interactions in a long-term (LTE) and short-term (STE) field experiments.

Experiment	Source of variation	Crop residues (%)	Grain yield (kg ha^{-1})	Crop biomass (kg ha^{-1})
	Tillage (Till)	<0.01	ns	ns
LTE	**Date**	ns	-	-
	Till*Date	0.02	-	-
	Till	<0.01	ns	ns
STE	**Date**	ns	-	-
	Till*Date	0.03	-	-

ns, non significant.